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# A Holistic Approach to Risk Based Maintenance Scheduling for HV Cables

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**ABSTRACT** Regular maintenance inspection and testing is essential in extending cable life and reducing failure probability. This can be achieved by improving the conduit conditions and taking corrective actions on faulty cable components and accessories. Regulators and corporate governance among power utilities require the implementation of risk-based approaches to asset management. However, practitioners lack sufficient historical event data and knowledge that allow them to determine the failure probability of individual cable components, which is an essential component for risk assessment, due to that the high voltage (HV) cable population are relatively young, and many have not yet reached the end of their design life. This paper presents a novel holistic approach to allow the risk based maintenance strategy to be conveniently implemented for the cable conduit, cable terminations, joints, main bodies and the earthing systems separately for each cable circuit. Contributions include: (i) a failure frequency model which accounts for every past failure record of individual cable circuit components to approximate the probability of failure. This, when multiplying with the cable importance or failure consequence, yields the risk level of an individual cable component or a cable circuit; and (ii) a method of optimally scheduling the maintenance activities by setting the objective functions as the minimal cable system risk. The benefit of the simple failure frequency model has the advantage of not having to depend on human intervention and it does not need a large sample to generate valid results, as is the case with other statistical methods. Results of applying the proposed maintenance scheduling model to 21 selected High Voltage (HV) cable circuits show that the average risk can be significantly reduced while continuing with the same number of inspections and test operations.

**INDEX TERMS** Power cable, risk based maintenance, probability of failure, maintenance scheduling.

## I. INTRODUCTION

High Voltage (HV) and Medium Voltage (MV) power cables, which form the backbones of the urban electrical networks worldwide, are expensive to maintain and to replace. In China alone, the total length of HV and MV cables (above 10kV) stands at around 60,000 kilometres and is still rapidly increasing. The specialists involved in cable maintenance are in the dozens of thousands [1]. Cable faults contributed to the majority of customer lost minutes as it takes longer to locate and repair the underground cable systems comparing with other power plant items [2].

In theory, the life of a cable is dictated by insulation degradation due to electrical and thermal stresses [3], and the failure probability of a cable or cable population should obey the curve shown in Fig. 1(a), where the likelihood of failure is relatively low between the date of commissioning and a certain point in time when age related insulation degradation causes the failure probability to increase exponentially. However, in practice, cables often suffer from early mortality failures due to defects associated with manufacturing and installation processes. As a result, the curve of failure rate, or failure probability, of operational cable circuits has the shape shown in Fig. 1(b).

The shape parameters of the so-called bathtub curve vary with many factors, such as cable and accessory design, manufacturing quality, installation quality control and operational loading and environment. In fact, regular maintenance and inspection is essential in reducing failure probability at both ends of the bathtub curve. This can be done by improving the conduit conditions and taking corrective actions on faulty cable components and accessories. In order to improve the effectiveness of maintenance operations, the influence of these factors on the curve shape should be quantified and the point in time at which knee points occur in the curve should be determined.

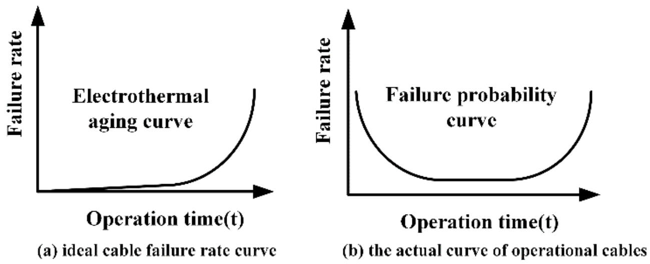


**FIGURE 1. Cable failure rate curves, (a) ideal cable failure rate curve, (b) the actual curve of failure probability of operational cables**

In the past, various strategies have been applied to maintenance management of electrical equipment [4]. These can be categorised as:

a) Corrective maintenance: Carried out following the detection of an anomaly and aimed at restoring normal operating conditions. This approach has never been given consideration among power utilities as failure to a key plant item may cause a major blackout which is economically and socially unacceptable.
b) Preventative or time based maintenance: Carried out at predetermined intervals or according to prescribed criteria, and is aimed at reducing the failure risk or performance degradation of equipment.
c) Condition based maintenance: Decisions with regard to the timing and amount of maintenance are dependent on the actual equipment condition (stage of deterioration). The equipment condition is continuously assessed by on-line condition monitoring. Maintenance is carried out when certain indicators give the signal that the equipment is deteriorating and the failure probability is increasing.
d) Risk based maintenance: Maintenance is carried out based on the level of risk which is defined as the multiplication of the probability of equipment failure and the consequence of the potential failure.

In power cable maintenance, the present regime is still largely time based. The current practice fails to consider the reliability or failure probability of an individual cable, e.g. length of service, route conditions, loading history and past failure statistics. Maintenance engineers are faced with the challenge of having to carry out routine testing on a rapidly increasing volume of cable assets, yet finding that a majority of the cable components are fault free when routine maintenance work is carried out.

Efforts have been made on condition based maintenance which, mainly centred on insulation condition, has not been applied with any great success despite developments in cable condition monitoring and testing techniques over the last 20 years. These include partial discharge [5], [6], Ultra-low frequency dielectric loss test for medium voltage cables [7], damped oscillatory wave test [8], and sheath current monitoring and infrared temperature measurement [9]. The authors' experience is that these expensive condition monitoring techniques can only help identify a small proportion of failure related problems. Also condition monitoring test results are often scattered, and there is often little correlation between what is diagnosed and what is found when a failed cable is examined [10], [11].

Despite recent developments in the area of maintenance optimisation such as the prescriptive maintenance [12], the direction of the maintenance strategy, as far as the current project funding body is concerned and among other power utilities, is the risk based approach [13]. Risk-based cable maintenance inspection, based on failure probability and failure consequence, may help to minimizing the asset risk level with the given resources, so making more effective use of asset engineers.

However, there is still a gap between the maintenance management aim and the practice, as practitioners lack sufficient historical event data and knowledge that allows them to assess the failure probability of individual cable components. This is due to that the high voltage (HV) cable population are relatively young, and have not yet reached the end of their design life of 30-40 years for polymeric XLPE cables, and 60-70 years for paper insulated PILC cables.

This paper provides an engineers' perspective on cable failure analysis and proposes a holistic approach to implement risk based maintenance scheduling. Section 2 summarises the current practice and discusses the shortcomings in cable maintenance. Section 3 presents a cable asset management structure, in accordance with international standard on asset management ISO55000, and proposes a holistic approach which itemises the failure probability and associated risk of the terminations, joints, earthing systems and the cable bodies, separately, of every circuit. Section 3 also provides a novel procedure for rescheduling inspection and maintenance work. Section 4 applies the optimization method for prioritising the maintenance activities to 21 selected high voltage circuits in the city of Zhuhai, China. Section 5 presents the conclusions and discusses the future research opportunities on the topic.

## II. CURRENT PRACTICE IN CABLE MAINTENANCE

### *A. Current practice in cable circuit inspection and maintenance*

In most metropolitan cities of China, cable maintenance engineers are set up as an independent work unit, with a given annual budget and a certain number of staff: the values are proportional to the number of cable circuits and their lengths. For each cable circuit, they carry out largely time based maintenance inspections, as illustrated in Fig. 2, on the cable conduit, terminals, joints, cable main body sections, and the earthing system which include the cable link boxes and earthing facilities. The periodicity of inspections and testings varies roughly with the importance of the circuit, as given in Table 1, which also gives more details of the contents of inspection and testing. It is to note that the periodicity given here is taken from a metropolitan city in South China. The practice may vary from region to region, and may change over time.

Although faults in the cable earthing system may not result directly in circuit outage, they may lead to failure via floating earth or accelerated aging through thermal effects due to increased sheath currents [9]. There are many examples of reported incidents in which theft of earthing conductors caused loss of earthing and, as a result, high potential on the metal sheath led to breakdown of the outersheath, which resulted in fire and damage to all cables in the same conduit. Therefore, the earthing system is a key component in the list of inspection and maintenance activities. Different cable installation methods cause different levels of ventilation and thermal conduction. Conditions in a conduit determine the ambient condition of a cable circuit which, in turn, affects the operational temperature of cables. In addition, when a joint is immersed in water, the probability of moisture ingress and failure has been found to be higher than in those working in dry environment. Conduit condition data will be essential for evaluating the failure probability of cable bodies and joints, hence this assessment is also an important part of cable circuit inspection and maintenance.

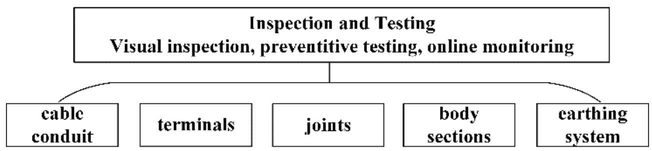


FIGURE 2. **Illustration of the objects of cable inspection and testings**

TABLE 1
THE CURRENT MAINTENANCE PERIODICITY OF HV CABLE CIRCUIT

| Item | | | Periodicity | | | |
|---|---|---|---|---|---|---|
| Classes of importance | | | I | II | III | IV |
| Cable conduit | visual inspection | Conduit, labelling, dangerous construction | Twice per week | Twice per week | Twice per month | Twice per month |
| | | Cable operational environment | | | | |
| | | Damage to cable body, terminations, joints and earthing facilities/ cable link box | Twice per month | Twice per month | Twice per month | Twice per month |
| Terminal/Joint | testing | Sheath current, PD one year after installation, every 3 years | 2 monthly | 2 monthly | 1) 6 monthly for 35kV, 110kV 2) 3 monthly for 220kV | 1) 6 monthly for 35kV, 110kV 2) 3 monthly for 220kV |
| | | Infra-red thermal check | | | | |
| Cable main body | testing | PD one year after installation, every /3 years | 2 monthly | 2 monthly | 1) 6 monthly for 35kV, 110kV 2) 3 monthly for 220kV | 1) 6 monthly for 35kV, 110kV 2) 3 monthly for 220kV |
| | | Infra-red thermal check | | | | |
| Earthing system | testing | Sheath circulating current | 2 monthly | 2 monthly | 6 monthly | 6 monthly |
| | | Insulation resistance testing | After installation of new circuit, and every 3-6 years in accordance with industrial standard. | | | |
| Others | Increased inspection/testing after extreme weather and on request from customer to guarantee supply for important occasions; Increased inspection when possibility of third party damage due to nearby construction work | | | | | |

### *B. Risk assessment: current practice*

Following the release of ISO 55000 [14], some power companies in China attempted an approach for cable circuit maintenance scheduling that is based on a risk index, as shown in Fig. 3, which is determined from a combination of a health index and an importance index. Both the health and importance indices are categorized as having four levels: i.e. “critical”, “important”, “caution” and “normal”. The importance of a circuit depends on the potential safety and economic consequence of the loss of the circuit and the voltage rating of the circuit. The importance can also be affected by the cable circuit location and nature of customer the circuit supplies. This is determined by network operators and is beyond the control of maintenance engineers. The health index is supposed to be determined by maintenance engineers, based on findings from inspection and testing results. However, cable maintenance engineers have yet to find an approach to effectively assess the health index. The maintenance inspections, of which a periodicity is shown in Fig. 2, are still carried out, largely, in a time based manner.

With regard to current practice, there are two shortcomings where improvements could be made. Firstly, due to poor practice in recording of past failure data, these failure events have not been fully analyzed to obtain the curves shown in Fig. 1. Nor has the data been used to underpin maintenance and replacement strategies, so as to prevent similar failures occurring in the future. Secondly, determination of indices relies on human input, as there is no numerical method that allows operational data and failure events to be taken into account, and that can schedule automatically and optimally the optimal maintenance activities. Due to a lack of detailed consideration of risk factors, a lot of manpower and resources have been wasted on unnecessary inspection and testing in the one hand. And in the other, failures may occur on circuits which have relatively high risk of failure which have received no timely interventions, resulting in unplanned outages.

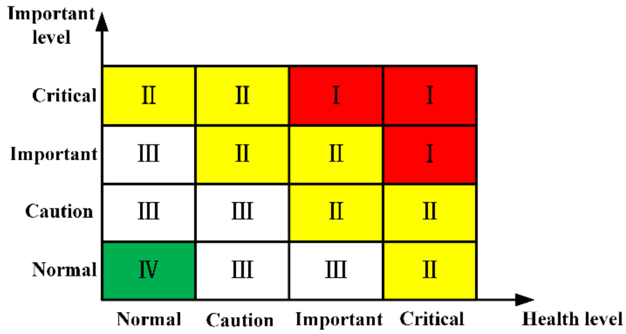


**FIGURE 3.** A cable criticality index matrix.

## III. THE PROPOSED HOLISTIC APPROACH TO RISK BASED MAINTENANCE SCHEDULING

### A. The aim and procedure of risk based maintenance scheduling

As outlined above, cable maintenance teams are constrained by budget and availability of specialist engineers. Within the context of asset management goals the maintenance team's aim is to minimize the risk in cable circuits in their geographical area. To achieve this aim requires a ranked list of risks, which may be obtained via a workflow diagram, such as that given in Fig. 4. The risk is assessed as the probability of failure multiplied with failure consequence. This procedure should be completed for the terminations, joints, cable bodies and earthing system components on every circuit. Based on the risk assessment outcome, the maintenance activities can then be rescheduled.

The procedure of the proposed holistic approach to risk based maintenance scheduling is illustrated in Fig. 5. The novelties include: (i) a failure frequency model which accounts for every past failure record of individual cable circuit components to approximate the probability of failure which, when multiplying with the cable importance or failure consequence, yields the risk level of an individual cable component or a cable circuit; and (ii) a method of optimally scheduling the maintenance activities by setting the objective functions as the minimal cable system risk. These will be detailed in the next section.

### B. A risk based model for optimization of cable maintenance activities

As discussed above, risk is the probability of failure multiplied with the consequence of failure. So far, there has been no report of a methodology which allows the probabilities of cable circuit failures to be quantified with limited data at hand for the condition of all cable circuit components. Such a model is developed and detailed in this Section. Nor has any effort been reported in risk based maintenance scheduling.

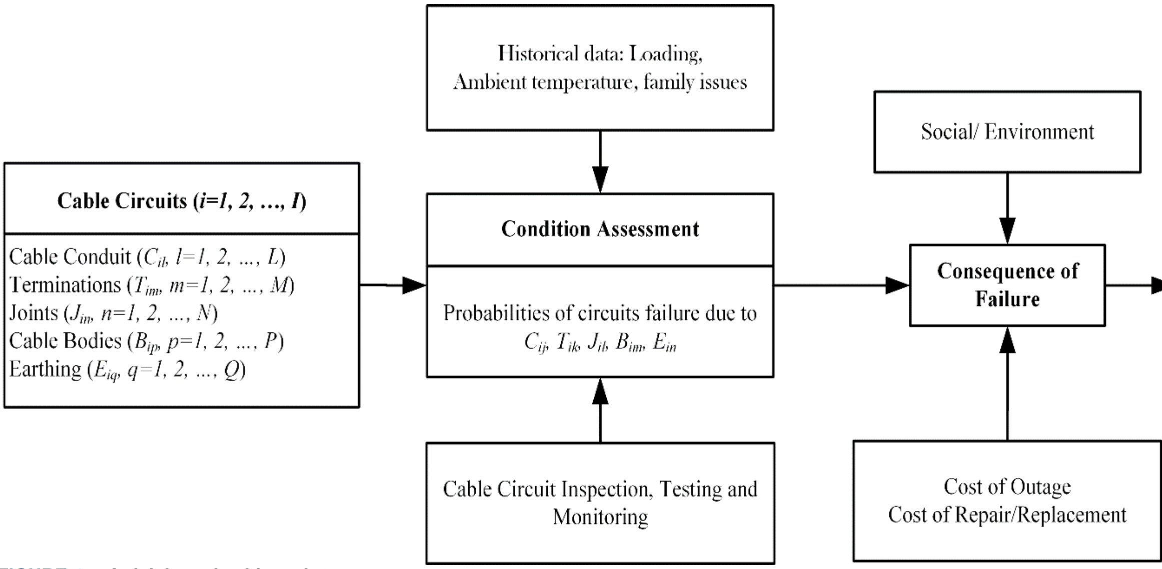


**FIGURE 4.** A risk based cable maintenance management structure

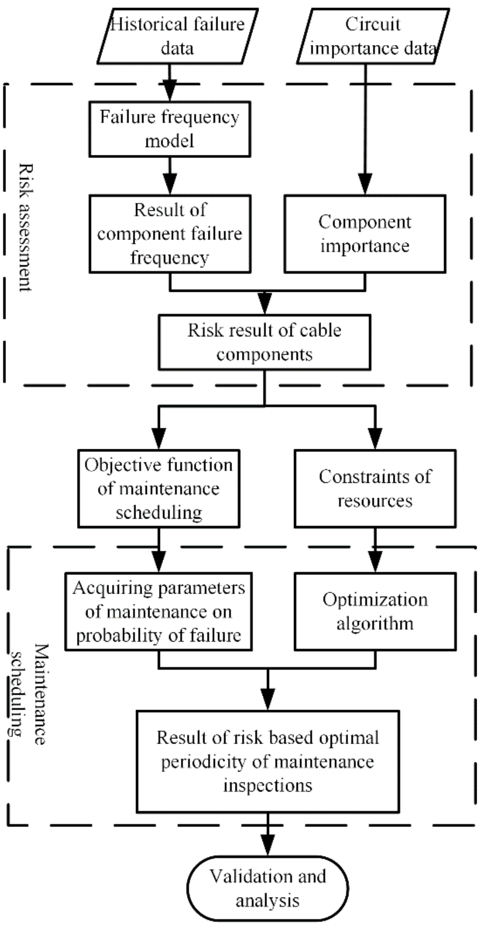


**FIGURE 5.** The procedure of the proposed holistic risk based approach

### 1) FAILURE FREQUENCY MODEL

To avoid over-complicating the mathematical model, and to have a model which is sufficiently robust while operating with limited data, the idea behind the Index of Failure Criticality (IFC) [15] is to be adopted in the proposed failure frequency model (FFM). The model divides the number of system failures caused by components of type $j$ over the time (0, $t$) by the total number of system failures in (0, $t$).

$$f_j(t) = \frac{n_j(t)}{FN} \tag{1}$$

where $n_j$ is the number of system failures caused by component $j$ and $FN$ is the Failure Number, i.e. the total number of system failures. Thus for every system failure which results from a defined component, the components failure count ($n_j$) is increased by one. $f_j(t)$ here stands for the criticality index of a system failure caused by component $j$.

In this paper, the proposed failure frequency model essentially records the frequency of failure determined from past failure events. It is an approximate to the failure probability of all 5 individual cable component types in each circuit, as listed below. A circuit may consist of a) a number of conduits of different types, b) have at least two terminals, c) have a number of cable joints, d) have a number of sections of cable bodies, which may be of different types of design, and e) have a number of cable link boxes and earthing electrodes in the earthing system. The failure probability of these 5 component types are each modelled as a function of time, $t$, as given in (2). For simplicity, $t$ is taken as the service age of a unit in years.

$$f_j(t) = \frac{n_j(t)}{FN} \quad j = 1,2,3,4,5 \tag{2}$$

Where, $f_1$, $f_2$, $f_3$, $f_4$ and $f_5$ represent failure probabilities associated with cable conduit, terminations, joints, bodies and earthing systems respectively. $n_1(t)$, $n_2(t)$, $n_3(t)$, $n_4(t)$ and $n_5(t)$ represent the number of cable failures due to issues related to cable conduit, termination, joints, body and earthing systems in each year of their service life. $FN$ stands for the total failure number, equal to the sum of all failures listed above.

The proposed method accounts for the frequency of component failures and is not the same, in terms of physical meaning, as the probability of failure determined using traditional statistics theory. However, as the failure records grow, the model output should progressively approach the result of failure probability.

The proposed model has the advantage of not depending on human intervention and does not need a large sample to large sample to generate valid results, as is the case with other statistical methods [16]. The system outputs updates every time a cable circuit failure event is recorded. As a result, the model responds to all manufacturing or installation problems for all component types, as well as problems due to local environmental conditions.

It is assumed that any defects which are detected or discovered during inspection and testing campaigns are repaired or the component is replaced. Therefore, data in relation to condition monitoring or testing is not included. It is also assumed here that the effect of loading level of a circuit on cable component failures is also manifested in the failure numbers and therefore will not be considered separately.

The model developed thus far will be illustrated in a case study in the next section, where further details of model implementation will be shown. With the simplified, holistic approach being presented, data required to determine the probability of failure of components can be readily obtained from records of past failure events. As the sample size increases, and additional information on failure component type and frequency is incorporated in the model, the accuracy of the model should steadily improve.

### 2) FAILURE CONSEQUENCE MODEL

Failure consequence of a network component has been known as component importance in power system reliability studies, e.g. [17]. Two streams of approach have been applied previously. One uses numerical models to quantify economic loss, the other is to holistically classify network component importance into four levels, based on voltage level and the location and nature of consumers being supplied. This paper focuses on failure probability and adopts the importance classification given in Fig. 3: it ranks each circuit to one of four importance levels, with a numerical value determined empirically by the present authors, as given in Table 2. Currently, the index is determined by network operators and is beyond the control of cable maintenance engineers.

TABLE 2
IMPORTANCE LEVELS OF HV CABLE CIRCUITS AND THEIR NUMERICAL VALUES.

| Importance level | Numerical value of the importance index |
|---|---|
| Critical | 1.0 |
| Important | 0.8 |
| Caution | 0.6 |
| Normal | 0.4 |

Note that, as all components in a cable circuit will have the same failure consequence, they share the same consequence result: therefore a difference in failure consequence only exists among different circuits.

### 3) CABLE COMPONENT RISK MODEL

By combining the models presented in the previous two subsections, the set of equations governing the cable component risk model is summarized in (3), where $I_i$ denotes the importance index of cable circuit $i$.

$$R_{ij} = f_j\left(t\right)\times I_i \quad j = 1,2,3,4,5 \tag{3}$$

Clearly, the risk result varies with the service age of cable components.

The risk of cable circuit $i$ can be determined as $R(i)$.

$$R\left(i\right) = R_{i1} + R_{i2} + R_{i3} + R_{i4} + R_{i5} = \sum_{j=1}^{5} R_{ij} \tag{4}$$

The average risk of all the cables $R$ in a region is therefore given as in (5), where $N$ represent the total number of circuits in the region under consideration.

$$R = \sum_{i=1}^{N} \frac{R\left(i\right)}{N} \tag{5}$$

### 4) MAINTENANCE SCHEDULING

In this section, it is assumed that maintenance of cable conduit requires inspections, while other components need inspection, testing and measurements, such as infrared imaging, sheath currents and partial discharge measurements.

Factors which are considered in the model are:

a) Only part of the overall failure number is detectable prior to the failure event. The percentage may be obtained from (6), where $n_{jd}$ represents the number of failures which may be detected using effective inspection and condition assessment techniques, e.g. infra-red imaging, sheath currents and partial discharge test, etc. $n_{jud}$ enumerates those faults which may not be detected because the site is not accessible for inspection or because there is no detectable electrical phenomena associated with them, e.g. moisture ingress, where eventual failure occurs due to thermal run-away.

$$n_j\left(t\right) = n_{jd} + n_{jud} \tag{6}$$

b) Of those defects which can be identified and diagnosed, all experience a growth period in which the defects deteriorate gradually. If the rate is sufficiently slow, some circuits can be restored to normal condition through actions by maintenance engineers without causing outages.

c) In the period under consideration, the interval between tests, the defect growth rate is assumed to remain constant. The percentage of defects being successfully restored to normal condition in the period is assumed as $\alpha$ and the percentage of defects converting to a failure is $\beta$.

With the following assumptions that the number of defects remaining after the first and second round of maintenance can be determined from (7) and (8): the growth rate of defect number is $k$, the periodicity of maintenance scheduled is $T$ ($kT$ is therefore the total number of defects at the end of period $T$), over the maintenance period $Y$ under consideration (assumed as $Y$=1 year in the paper), and that the success rate of removing a defect is $\alpha$, the number of defects remaining can be determined from (7) and (8) after the first and second round of maintenance.

$$m_{1T} = (1-\alpha)kT \tag{7}$$

$$m_{2T} = (1-\alpha)(m_{1T} + kT) \tag{8}$$

After $h$ maintenance operations, the number of defects remaining is therefore given by (9).

$$m_{hT} = (1-\alpha)\left(m_{(h-1)T} + kT\right) = \frac{(1-\alpha)\left[1-(1-\alpha)^h\right]kT}{\alpha} \tag{9}$$

Here, $h = \frac{Y}{T}$, the frequency of maintenance.

Clearly the number of failures that will occur during an inspection period, in this case one year, will depend on the periodicity of the maintenance scheduling. In Fig. 6, the effect on the number of defects remaining if there is no scheduled maintenance is contrasted with maintenance being scheduled every 2 months and every 4 months.

The corresponding number of failures can therefore be obtained from (10).

$$n_{hT} = \beta m_{hT} = \frac{(1-\alpha)\left[1-(1-\alpha)^h\right]\beta kT}{\alpha} \tag{10}$$

Based on (5) and (10), the objective function of minimizing the risk of a group of cable circuits can then be expressed in (11), from which the optimal maintenance activities can be scheduled. Here, again, $Y$ stands for the maintenance scheduling period under consideration.

$$\begin{aligned} min\, R &= \min \sum_{i=1}^{N} \frac{R(i)}{N} \\ &= min \sum_{i=1}^{N}\sum_{j=1}^{5} \frac{(1-\alpha)\left[1-(1-\alpha)^{\frac{Y}{T_{ij}}}\right]\beta k T_{ij}}{\alpha N} I_i \end{aligned} \tag{11}$$

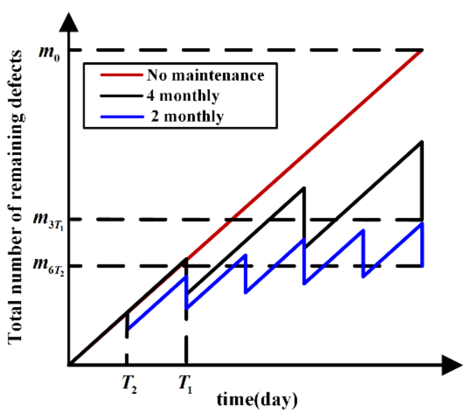


**FIGURE 6. Total number of defects remaining as a function of time between scheduled maintenance.**

This optimization procedure should be subject to the constraints of overall workload after the optimization value $W_p$ is equal to the workload before optimization, namely $W_0$. Here $T_{ija}$ and $T_{ijb}$ represent the inspection period of cable conduits and condition tests of cable bodies and accessories respectively. The total workload is given by (12), where it is taken into account that the time required to carry out an inspection of a cable conduit is approximately a quarter of that required to carry out condition assessment tests on cable bodies, joints, terminations and earthing systems. The latter also includes the time required for data analysis.

$$W = \sum_{i=1}^{N}\sum_{j=1}^{5}\left(\frac{Y}{4T_{ija}} + \frac{Y}{T_{ijb}}\right) \tag{12}$$

## IV. CASE STUDIES

### A. Historic failure events

Data on failure events which occurred on HV (110kV and 220kV) cable circuits have been collected from 4 metropolitan cities in South China. Events for which the failure causes could not be identified have been removed from the investigation. Table 3 provides details of the 86 failure events for which cause could be assigned. For all the events where the failure causes were identified, the failure probabilities of all 5 components were determined using the model proposed in the paper: the data is presented in Fig. 7. Clearly, the probability of failure in joints and terminations in the first 5 years are the highest, and there has, as yet, been no sign of age related failures.

### B. Application of the risk model to 21 selected HV cable circuits

To demonstrate the applicability of the proposed optimal maintenance scheduling model in practical situations, 21 HV circuits from a metropolitan city in Southern China have been selected as a case study. The basic information and the importance index assigned to the 21 circuits are listed in Table 4: the importance indices were classified into 4 levels and assigned numerical values by the system operators.

#### 1) THE CURRENT MAINTENANCE SCHEDULE AND THE ASSOCIATED RISK LEVEL

As described in Section II of this paper, the periodicity of the current maintenance schedule can be determined from data provided in Table 1 and Table 4.

The risk levels of the circuits (without optimisation) can be determined using (3) - (5) presented in Section III of the paper. The result is obtained in (13) and is illustrated in Fig. 8.

Using (12) and taking the periodicity of inspection from Table 1, the total maintenance work load W0 can be calculated, as shown in (14) below.

$$R_0 = \sum_{i=1}^{21}\sum_{j=1}^{5}\frac{R_{ij}}{N} = 0.0587 \tag{13}$$

$$
\begin{aligned}
W_0 &= \sum_{i=1}^{21}\sum_{j=1}^{5}\left(\frac{Y}{4T_{ija}}+\frac{Y}{T_{ijb}}\right) \\
&= \sum_{i=1}^{21}\frac{Y}{4T_{i1}}+\frac{Y}{T_{i2}}+\frac{Y}{T_{i3}}+\frac{Y}{T_{i4}}+\frac{Y}{T_{i5}} = 382/annum
\end{aligned} \tag{14}
$$

### 2) OPTIMISATION OF THE MAINTENANCE SCHEDULE

Based on the maintenance scheduling model proposed in Section III, the aim of the optimisation is to minimise the average risk level of the 21 circuits. Using (11), this can be achieved by re-scheduling the maintenance periodicity, with the available man power in man-days $W_0$ as constraints.

The parameters used for optimal scheduling is provided in (15), where the proportion of defects being restored to good condition during inspection and testing campaigns, or the value of $\alpha$, is assumed as 30%. The remaining number of faults, or the value of $\beta k_{ij}$, can be determined using equation (10).

By applying (15) below to the 21 cable circuits, the rescheduled periodicity of maintenance can be obtained. This is given in Table 5, as well as illustrated in Fig. 9.

$$
min\, R = min\sum_{i=1}^{21}\sum_{j=1}^{5}\frac{(1-\alpha)\left[1-(1-\alpha)^{n_{ij}}\right]\beta k_{ij}T_{ij}I_i}{\alpha FN\cdot N}
$$

$$
s.t.\begin{cases}
\sum_{i=1}^{21}\frac{Y}{4T_{i1}}+\frac{Y}{T_{i2}}+\frac{Y}{T_{i3}}+\frac{Y}{T_{i4}}+\frac{Y}{T_{i5}} \le W_0 = 382 \\
T_{i1} \le 30 \\
T_{i2} \le 183\ ;\ T_{i3} \le 183\ ;\ T_{i4} \le 183\ ;\ T_{i5} \le 183
\end{cases} \tag{15}
$$

### 3) OBSERVATIONS AND DISCUSSIONS

As shown in Table 5, the maintenance periodicity has significantly increased for circuits 1 to 10, all of which have relatively young service ages. This is because the proposed model considered that the probability of failure is much higher during the first 5 years than after the period. This can be expanded upon by comparing the data for circuits 3 and 13 before and after optimisation, as shown in Table 6. The optimisation model considers that circuit 3 has only been in service for one year and therefore has a higher probability of failure: after optimisation the periodicity of testing of terminals and joints has been reduced to once a month from the original every other month. In comparison, circuit 13 has been in service for seven years, the periodicity of the circuit route and conduit inspection has been extended from twice a month to once a month and maintenance tests changed from 2 monthly to 6 monthly, to reflect its lower probability of failure. For the selected 21 cable circuits, as shown in Table 7, application of the proposed optimisation model has reduced the average risk from 0.0587 to 0.0410 whilst the required total workload is almost unchanged. This is equivalent to that a 30.2% ((0.0587-0.0410)/0.0587) of the failure risk (the number of failures multiplied with their circuit importance) could have been avoided with the proposed model.

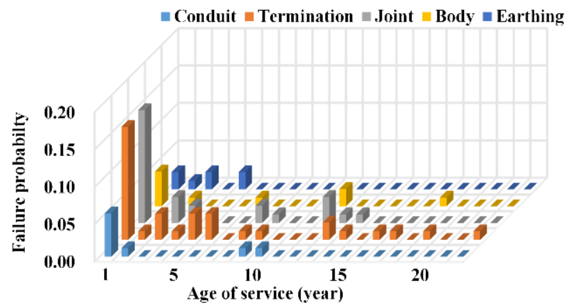


FIGURE 7. Failure probabilities of 5 cable component types, obtained using the proposed model

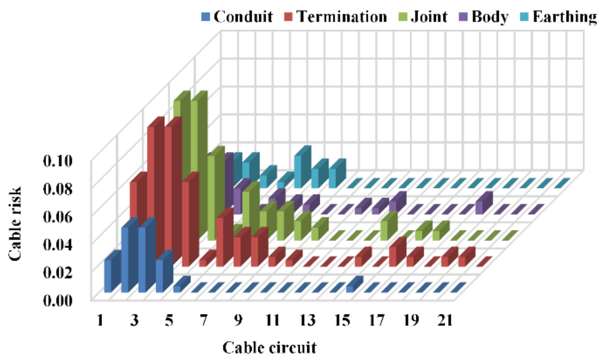


FIGURE 8. The risk level assigned to the 21 cable circuits before optimisation

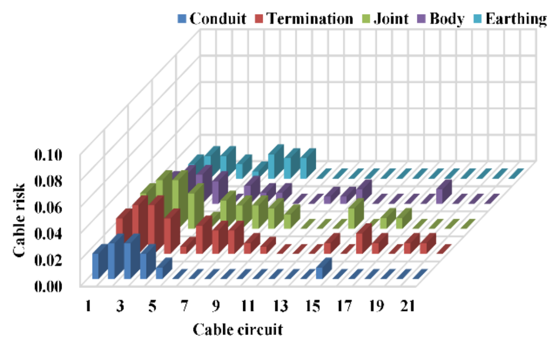


FIGURE 9. The risk level assigned to the 21 cable circuits after optimisation

TABLE 3
BREAKDOWN ANALYSIS OF PAST HV CABLE FAILURE EVENTS

| Duration of Service | Body | Joint | termination | Earthing system | Conduit | Total |
|---|---|---|---|---|---|---|
| 1 | 4 | 13 | 13 | 2 | 5 | 37 |
| 2 | 0 | 1 | 1 | 1 | 1 | 4 |
| 3 | 1 | 3 | 3 | 2 | 0 | 9 |
| 4 | 0 | 2 | 1 | 0 | 0 | 3 |
| 5 | 0 | 1 | 3 | 2 | 0 | 6 |
| 6 | 0 | 0 | 3 | 0 | 0 | 3 |
| 7 | 1 | 0 | 0 | 0 | 0 | 1 |
| 8 | 0 | 2 | 1 | 0 | 0 | 3 |
| 9 | 0 | 1 | 1 | 0 | 1 | 3 |
| 10 | 0 | 0 | 0 | 0 | 1 | 1 |
| 11 | 1 | 0 | 0 | 0 | 0 | 1 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 12 | 2 | 3 | 0 | 0 | 0 | 5 |
| 13 | 0 | 1 | 2 | 0 | 0 | 3 |
| 14 | 0 | 1 | 1 | 0 | 0 | 2 |
| 15 | 0 | 0 | 0 | 0 | 0 | 0 |
| 16 | 0 | 0 | 1 | 0 | 0 | 1 |
| 17 | 0 | 0 | 1 | 0 | 0 | 1 |
| 18 | 1 | 0 | 0 | 0 | 0 | 1 |
| 19 | 0 | 0 | 1 | 0 | 0 | 1 |
| 20 | 0 | 0 | 0 | 0 | 0 | 0 |
| 21 | 0 | 0 | 0 | 0 | 0 | 0 |
| 22 | 0 | 0 | 1 | 0 | 0 | 1 |
| Total | 10 | 28 | 33 | 7 | 8 | 86 |

TABLE 4
BASIC DATA AND IMPORTANCE INDEX OF 21 SELECTED HV CABLE CIRCUITS

| Circuit index | Voltage rating/kV | Service age/years | Importance index | criticality index |
|---|---|---|---|---|
| 1 | 110 | 1 | 0.4 | IV |
| 2 | 220 | 1 | 0.8 | III |
| 3 | 220 | 1 | 0.8 | III |
| 4 | 110 | 1 | 0.4 | IV |
| 5 | 220 | 2 | 0.4 | IV |
| 6 | 220 | 3 | 1 | II |
| 7 | 110 | 3 | 0.6 | III |
| 8 | 110 | 3 | 0.6 | III |
| 9 | 220 | 4 | 0.6 | III |
| 10 | 220 | 4 | 0.4 | III |
| 11 | 110 | 7 | 0.4 | III |
| 12 | 110 | 7 | 0.4 | IV |
| 13 | 110 | 7 | 0.8 | III |
| 14 | 110 | 8 | 0.6 | III |
| 15 | 110 | 10 | 0.4 | IV |
| 16 | 110 | 13 | 0.6 | III |
| 17 | 110 | 14 | 0.6 | III |
| 18 | 110 | 18 | 0.8 | II |
| 19 | 110 | 19 | 0.6 | III |
| 20 | 110 | 22 | 0.6 | III |
| 21 | 110 | 23 | 1 | III |

TABLE 5
THE OPTIMISED PERIODICITY OF MAINTENANCE SCHEDULES FOR THE 21 CIRCUITS

| Circuit index | Service age (years) | Importance index | Periodicity of maintenance（day） | | | | |
|---|---|---|---|---|---|---|---|
| | | | Conduit | Termination | Joint | Body | Earthing system |
| 1 | 1 | 0.4 | 11 | 36 | 36 | 100 | 182 |
| 2 | 1 | 0.8 | 8 | 25 | 25 | 50 | 100 |
| 3 | 1 | 0.8 | 8 | 24 | 25 | 50 | 100 |
| 4 | 1 | 0.4 | 12 | 37 | 37 | 100 | 182 |
| 5 | 2 | 0.4 | 26 | 182 | 182 | 182 | 182 |
| 6 | 3 | 1.0 | 31 | 54 | 54 | 182 | 78 |
| 7 | 3 | 0.6 | 31 | 87 | 87 | 182 | 158 |
| 8 | 3 | 0.6 | 31 | 87 | 87 | 182 | 182 |
| 9 | 4 | 0.6 | 31 | 182 | 158 | 182 | 182 |
| 10 | 4 | 0.4 | 31 | 182 | 182 | 182 | 182 |
| 11 | 7 | 0.4 | 31 | 182 | 182 | 182 | 182 |
| 12 | 7 | 0.4 | 31 | 182 | 182 | 182 | 182 |
| 13 | 7 | 0.8 | 31 | 182 | 182 | 182 | 182 |
| 14 | 8 | 0.6 | 31 | 182 | 158 | 182 | 182 |
| 15 | 10 | 0.4 | 26 | 182 | 182 | 182 | 182 |
| 16 | 13 | 0.6 | 31 | 158 | 182 | 182 | 182 |
| 17 | 14 | 0.6 | 31 | 182 | 182 | 182 | 182 |
| 18 | 18 | 0.8 | 31 | 182 | 182 | 182 | 182 |
| 19 | 19 | 0.6 | 31 | 182 | 182 | 182 | 182 |
| 20 | 22 | 0.6 | 31 | 182 | 182 | 182 | 182 |
| 21 | 23 | 1.0 | 31 | 182 | 182 | 182 | 182 |
| Average risk | | | | 0.0410 | | | |

TABLE 6
COMPARISON BETWEEN CIRCUIT 3 AND 13 BEFORE AND AFTER OPTIMISATION

| Circuit | | Risk | | Periodicity of maintenance | |
|---|---|---|---|---|---|
| | | Before optimisation | After optimisation | Before optimisation | After optimisation |
| Circuit 3 | conduit | 0.0465 | 0.0270 | 2 weeks | 8 days |
| | termination | 0.1210 | 0.0369 | 6 months | 25 days |
| | joint | 0.1210 | 0.0369 | 6 months | 25 days |
| | body | 0.0372 | 0.0220 | 6 months | 50 days |
| | earthing | 0.0186 | 0.0171 | 6 months | 100 days |
| Circuit 13 | conduit | 0 | 0 | 2 weeks | 31 days |
| | termination | 0 | 0 | 2 months | 182 days |

| | | | | |
|---|---|---|---|---|
| joint | 0 | 0 | 2 months | 182 days |
| body | 0.0093 | 0.0109 | 2 months | 182 days |
| earthing | 0 | 0 | 2 months | 182 days |

TABLE 7
RESULT OF OPTIMAL MAINTENANCE SCHEDULE

| Maintenance strategy | Workload | Average risk |
|---|---|---|
| Current schedule | 382 | 0.0587 |
| Optimised schedule | 382 | 0.0410 |

## V. DISCUSSION AND CONCLUSIONS

In the past, due to a lack of detailed consideration of risk factors, a lot of man power and resources have been wasted on unnecessary inspection and testing. These additional interventions add risk to the operation of the circuits, e.g. during off-load testing and recommissioning of the circuit to power system operation.

This paper proposed a holistic approach to modelling of failure probability and scheduling of maintenance activities, whereby cable circuits are considered as being divided into component types, i.e. cable conduit, terminations, joints, cable bodies and earthing systems. The proposed method calculates their respective failure probability based on records of past failure events and then reschedules the maintenance activities to minimize the risk level of all cable circuits under consideration.

The holistic failure probability model proposed in the paper enjoys the benefit of robustness as it works with small failure sample size, and without any failures at all. It updates every time a cable circuit failure event is recorded, and responds to any changes in the failure behaviour between regions, and over time. Based on the failure probability, the maintenance activities can be scheduled using the model presented in the paper to reduce the average risk of the cable population.

In general, HV cable circuits have proved very reliable, however, by scheduling more frequent maintenance on the circuits with higher risk and reducing the maintenance frequency on less risky assets, the proposed approach can help maintenance engineers to improve their productivity, or to improve their cable system reliability with the same amount of effort. Results showed that by applying the proposed model to schedule maintenance, the risk of cable failures could be reduced by 30.2% with the same amount of maintenance workload.

In some situations, as far as the authors are concerned, the cable population increases very rapidly, so much so that the cable maintenance resources are seriously stretched in dealing with the failure repair work and routine inspection and testing activities. In this case, an alternative objective may be set to minimize the total effort required for a given cable population, while keeping the risk at an acceptable level.

As the failure event records grow, the model may be further improved to account for environmental effects such as ambient temperature and moisture on failures. This may be achieved by modifying the failure probability model to allow monthly failures to be considered. As data records grow, further maintenance optimisation [12] may also be introduced to improve practice in the industry.

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